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(54) **PARTICLE SEPARATION**

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(51) **Int. Cl.**
B03C 3/011 (2006.01)

(52) **U.S. Cl.** **95/31**; 73/865.5; 95/69; 95/73; 95/78; 95/79; 96/57; 96/74; 96/75; 96/77; 209/127.1; 209/131

(58) **Field of Classification Search** 95/2, 3, 95/31, 32, 63, 69, 73, 78, 79, 58, 60; 96/18, 96/19, 26, 57, 74, 75, 77, 27, 80; 55/462; 209/127.1, 129, 131; 73/865.5
See application file for complete search history.

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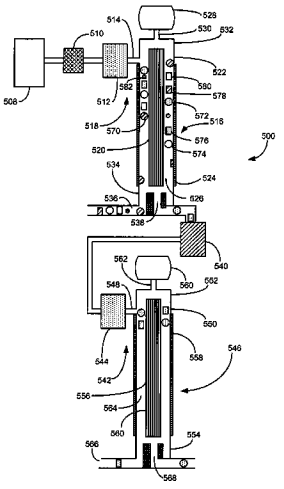
(57) **ABSTRACT**

Embodiments of a method for selecting particles, such as based on their morphology, is disclosed. In a particular example, the particles are charged and acquire different amounts of charge, or have different charge distributions, based on their morphology. The particles are then sorted based on their flow properties. In a specific example, the particles are sorted using a differential mobility analyzer, which sorts particles, at least in part, based on their electrical mobility. Given a population of particles with similar electrical mobilities, the disclosed process can be used to sort particles based on the net charge carried by the particle, and thus, given the relationship between charge and morphology, separate the particles based on their morphology.

20 Claims, 8 Drawing Sheets



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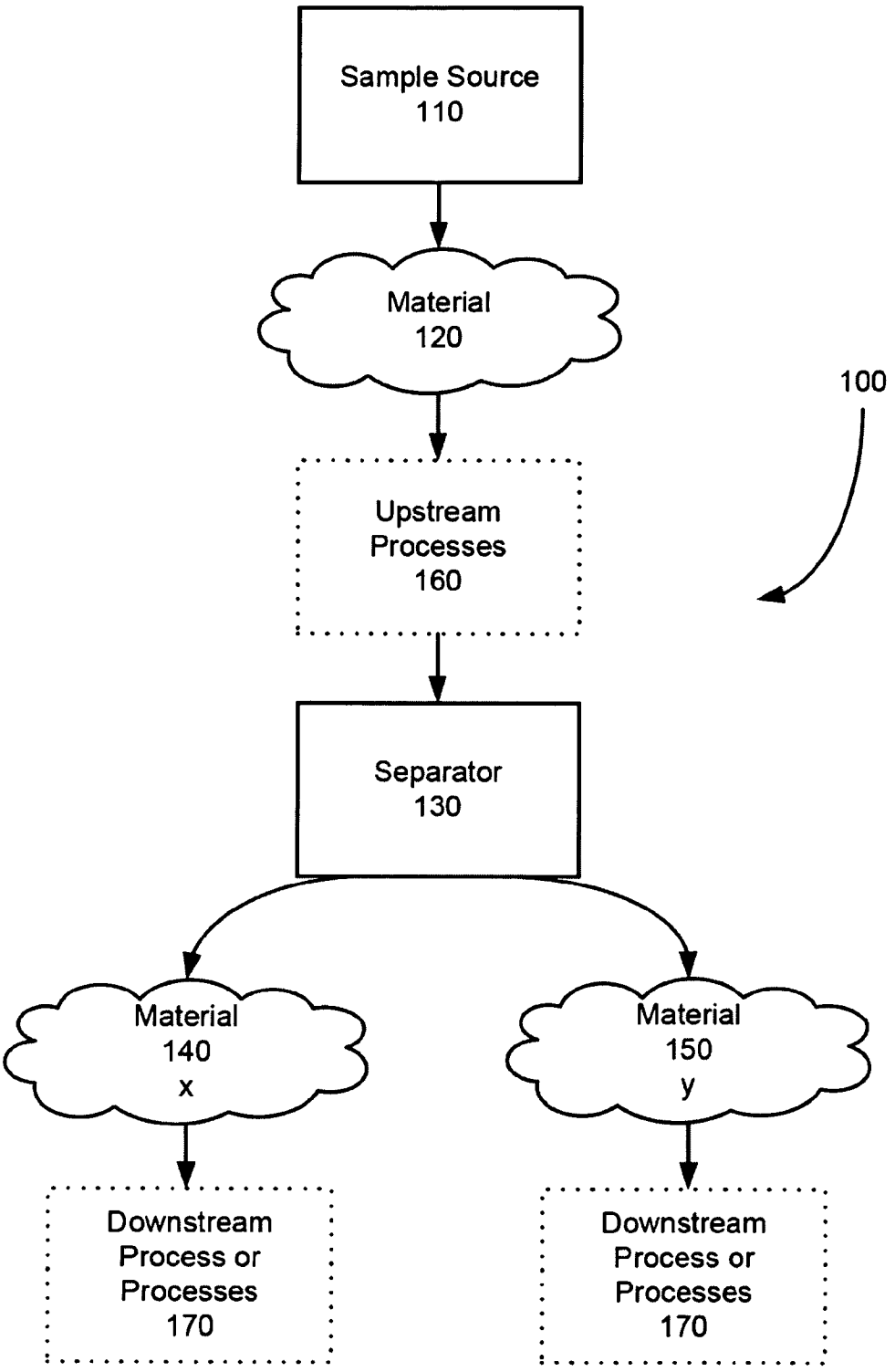
Sample Source
110
Material
120
100
Upstream
Processes
160
Separator
130
Material
140
x
Material
150
y
Downstream
Process or
Processes
170
Downstream
Process or
Processes
170

FIG. 1

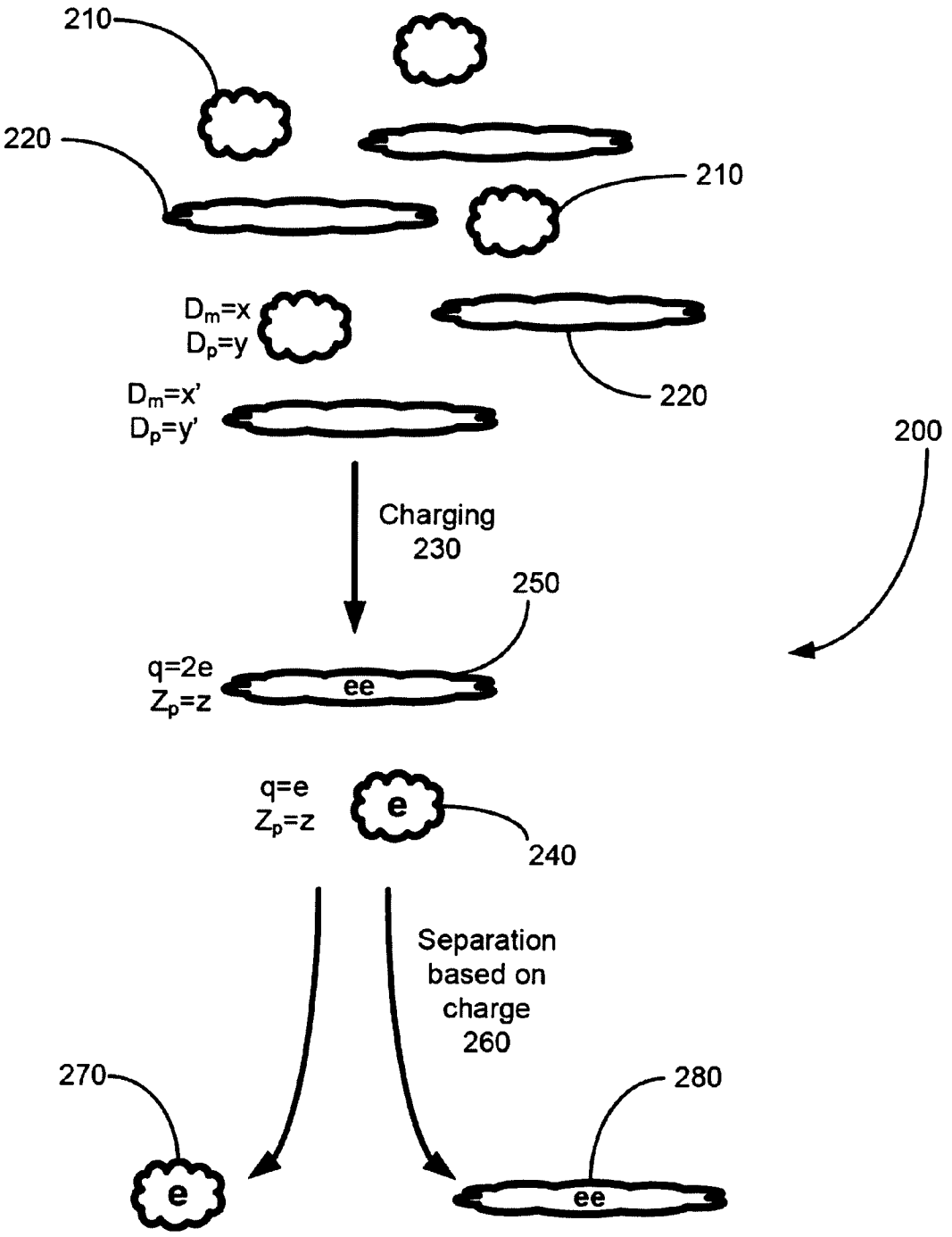
210
220
210
D_m=x
D_p=y
220
D_m=x'
D_p=y'
200
Charging
230
250
q=2e
Z_p=z
ee
q=e
Z_p=z
e
240
Separation
based on
charge
260
270
280
e
ee

FIG. 2

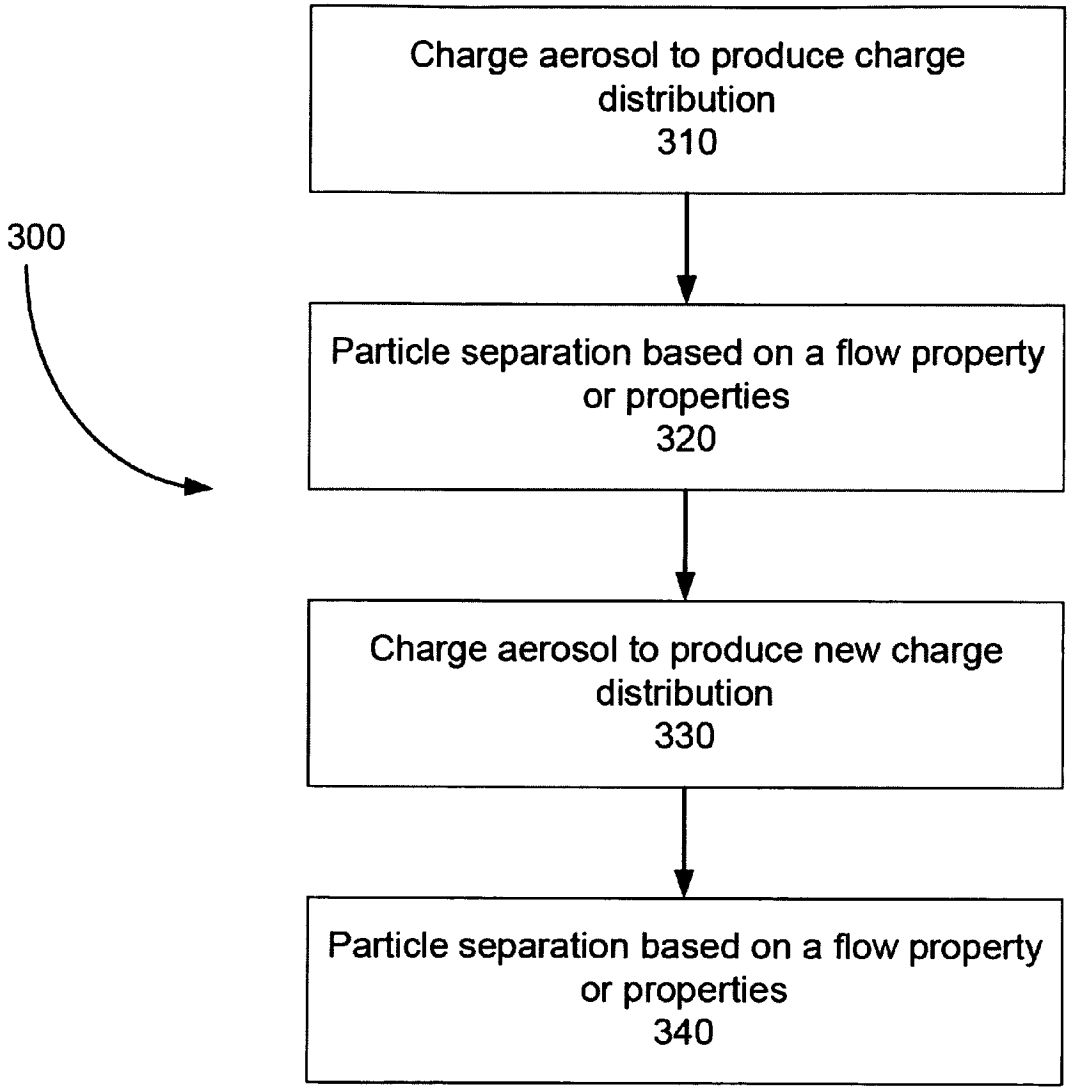
300
Charge aerosol to produce charge distribution
310
Particle separation based on a flow property or properties
320
Charge aerosol to produce new charge distribution
330
Particle separation based on a flow property or properties
340

FIG. 3

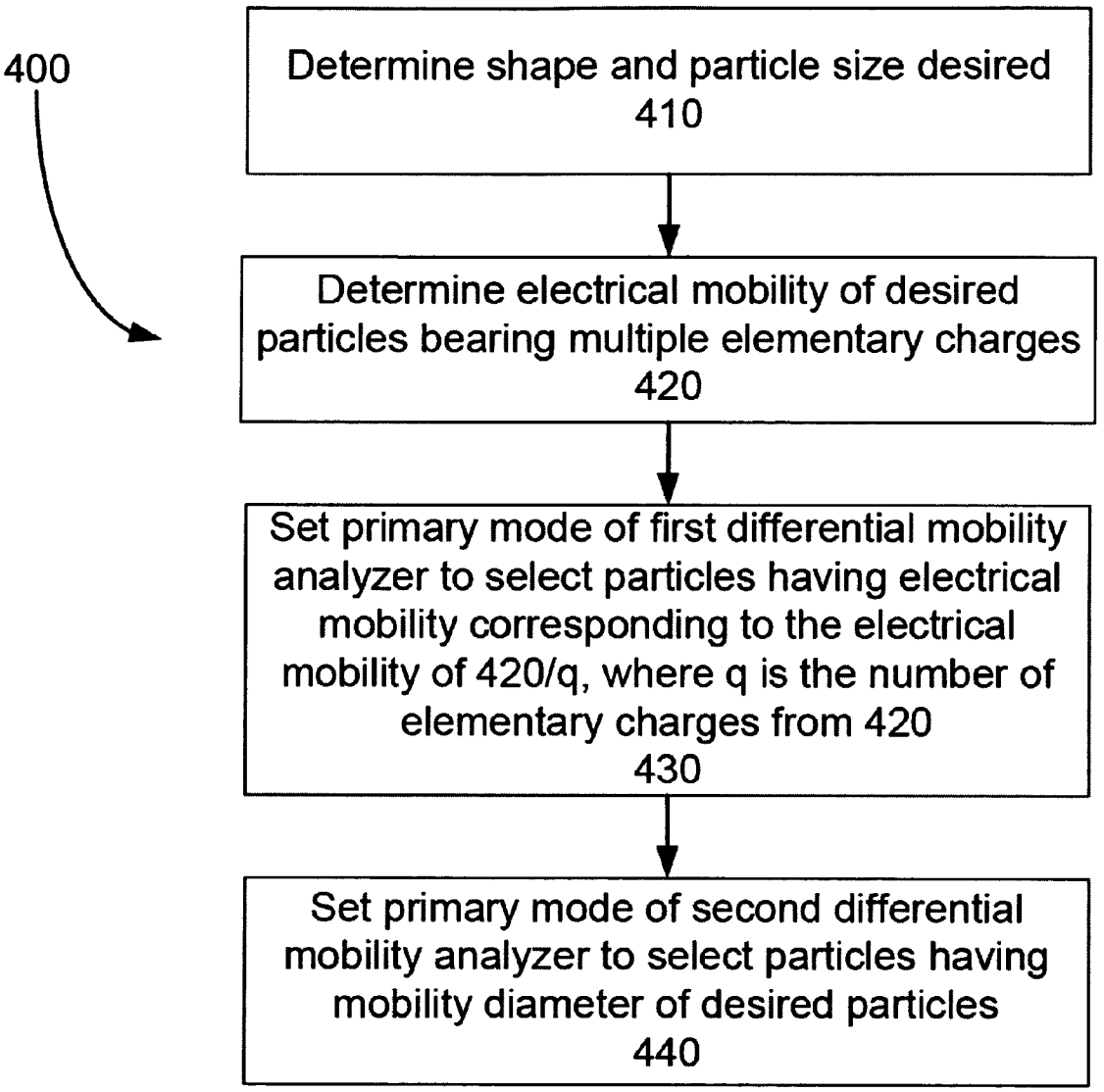
400
Determine shape and particle size desired
410
Determine electrical mobility of desired particles bearing multiple elementary charges
420
Set primary mode of first differential mobility analyzer to select particles having electrical mobility corresponding to the electrical mobility of 420/q, where q is the number of elementary charges from 420
430
Set primary mode of second differential mobility analyzer to select particles having mobility diameter of desired particles
440

FIG. 4

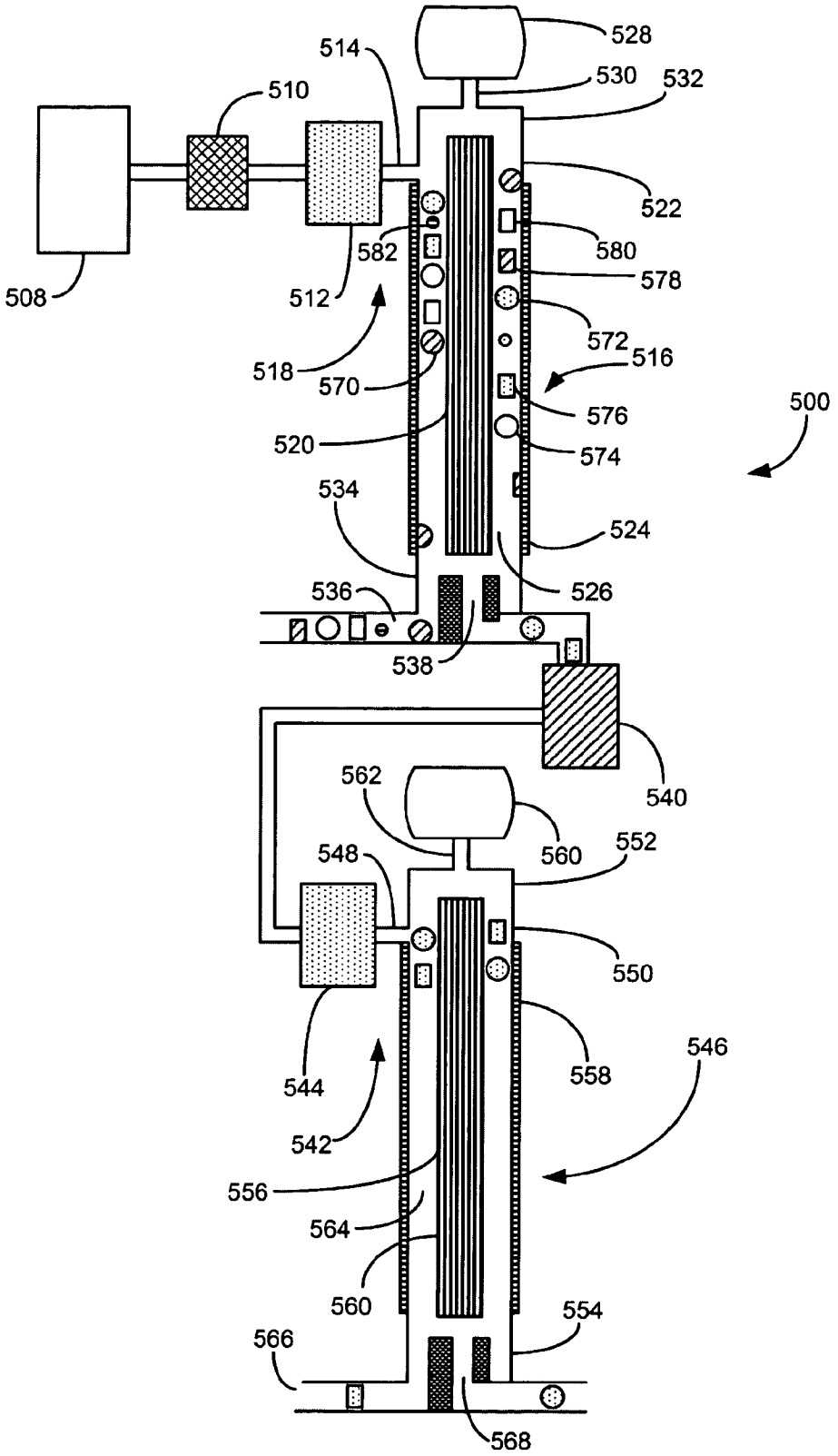
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FIG. 5

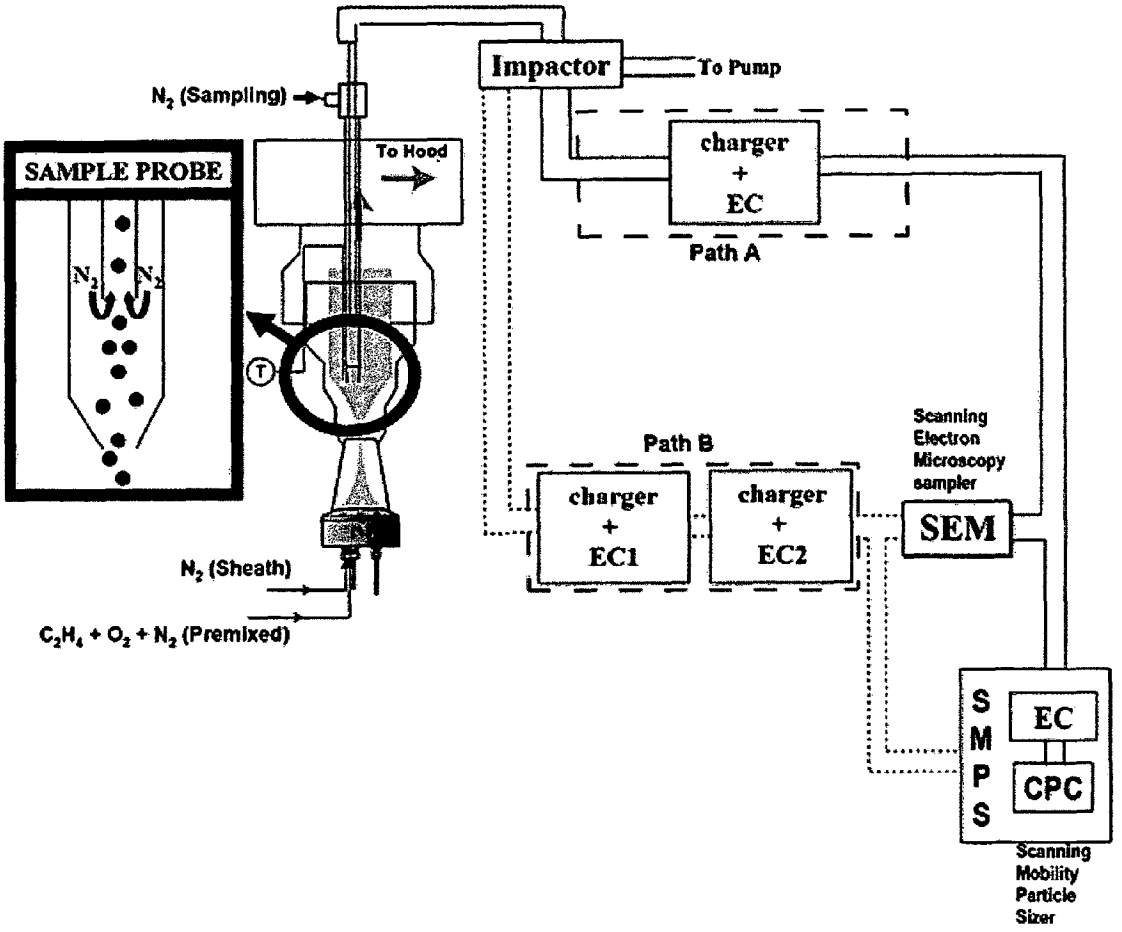
Impactor
To Pump
N_2 (Sampling)
SAMPLE PROBE
To Hood
charger + EC
Path A
N_2
N_2
T
Path B
charger + EC1
charger + EC2
Scanning Electron Microscopy sampler
SEM
N_2 (Sheath)
$C_2H_4 + O_2 + N_2$ (Premixed)
S M P S
EC
CPC
Scanning Mobility Particle Sizer

Fig. 6

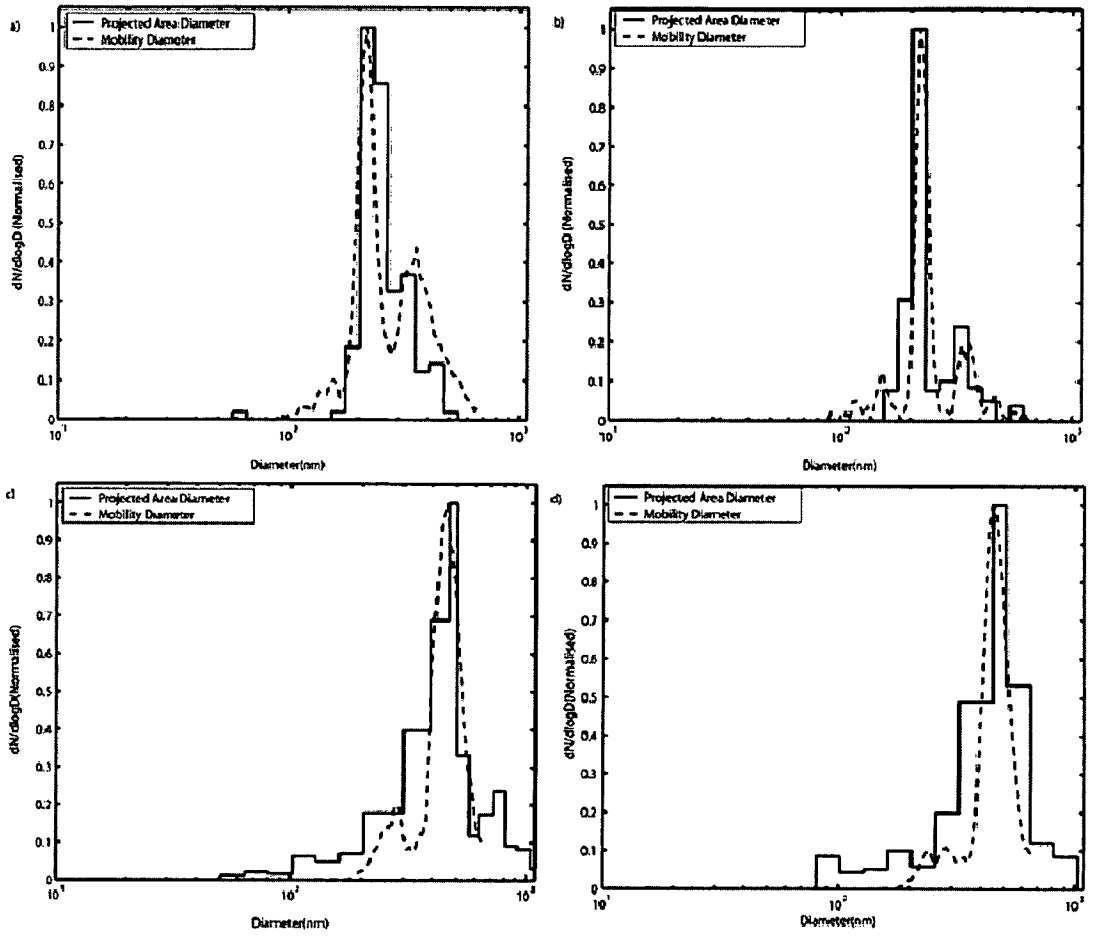
a)
Projected Area Diameter
Mobility Diameter
dN/dlogD (Normalised)
Diameter(nm)
b)
Projected Area Diameter
Mobility Diameter
dN/dlogD (Normalised)
Diameter(nm)
c)
Projected Area Diameter
Mobility Diameter
dN/dlogD(Normalised)
Diameter(nm)
d)
Projected Area Diameter
Mobility Diameter
dN/dlogD(Normalised)
Diameter(nm)

Fig. 7

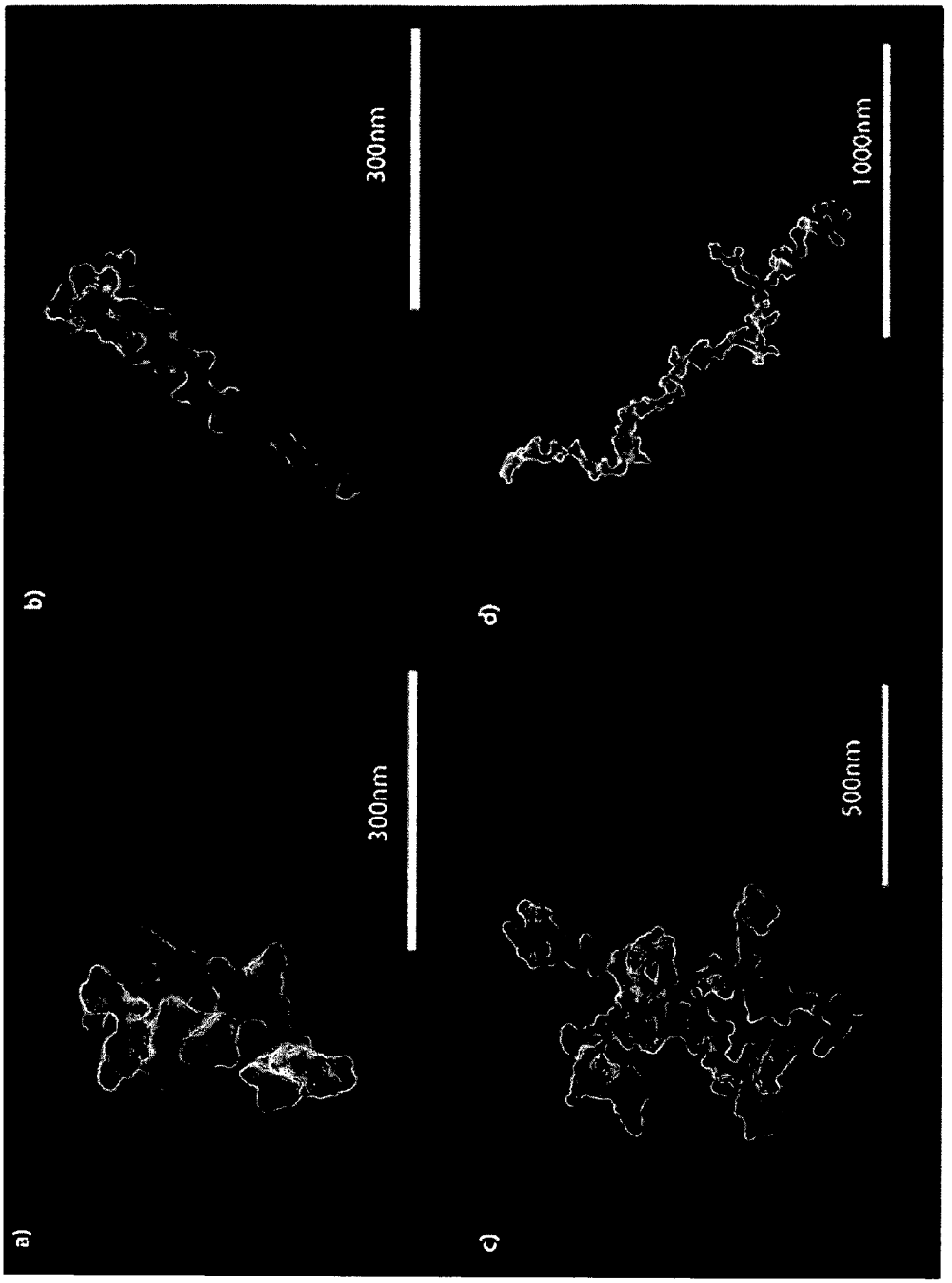

Fig. 8

PARTICLE SEPARATION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of, and incorporates by reference, U.S. Provisional Patent Application No. 60/968,835, filed Aug. 29, 2007.

STATEMENT OF GOVERNMENT SUPPORT

This invention was made with United States Government support under grants from the U.S. Department of Energy Atmospheric Science Program, grants DE-FG02-05ER64008, DE-FG02-98ER62581, and DE-FG02-05ER63995; the National Air and Space Administration (NASA) Upper Atmosphere Research Program, contract NAG2-1462, and Atmospheric Chemistry Program contract NNH04CC09C; and the National Science Foundation, grant Nos. ATM-0212464, ATM-0525355, and 0447416. The United States Government has certain rights in the invention.

FIELD

The present disclosure relates, generally, to a method and system for separating particles having different morphologies or flow properties. In a specific example, particles are separated based on their electrical mobility.

BACKGROUND

Morphology can be an important property in particle-related applications. For example, morphology may be a factor in aerosol synthesis, which can be used for bulk production of nanomaterials, such as in—1) pharmaceuticals synthesis and processing, where the ability to control the size and state of agglomerates can influence their behavior in the human body; 2) synthesis of printer toners, tires, paints, fillers, and fiber-optics products, where nanopowders morphology uniformity can influence product quality; and 3) carbon nanotube manufacturing, where uniformly sized and shaped carbon nanotubes may have desirable properties.

When used to produce particles beyond a certain length, aerosol formation mechanisms can produce agglomerates. Agglomerates can have complex, fractal-like morphologies, and particles having the same mass, such as being composed of the same number of individual particles, can have different morphologies, such as being more spherically or more linearly shaped. Segregating agglomerate ensembles based on their morphology can be difficult; there is no well-established technique.

SUMMARY

The present disclosure provides a method for separating particles having different morphologies based on their flow properties, such as their electrical mobility. In a specific embodiment, the aerosol is charged, such as with a bipolar charger, before the particles are separated based on their flow properties. In one example, charging produces at least a first distribution of a flow property and the particles are separated based on the first distribution. In a more specific example, the separated particles are charged again to produce at least a second distribution of a flow property. The separated particles are further separated based on the second distribution.

In an implementation of this example, an aerosol having a plurality of particle morphologies is charged. Particles having a first electrical mobility-to-charge ratio are separated from particles having a second electrical mobility-to-charge ratio. The particles of the first electrical mobility-to-charge ratio are selected particles. A charge is applied to the selected particles to produce particles having a first morphology and a first electrical mobility and particles having a second morphology and a second electrical mobility. The particles of the first electrical mobility are separated from particles having the second electrical mobility.

In a more particular implementation of this example, particles having the first and second electrical mobility-to-charge ratios are separated using a differential mobility analyzer. In a more particular implementation, particles having the first and second electrical mobilities are also separated using a differential mobility analyzer.

According to another configuration, the first electrical mobility corresponds to the product of the first electrical mobility-to-charge ratio and the number of elementary charges of the multiply-charged particles.

In further examples, the method includes size selecting particles in the aerosol prior to separating the particles based on their flow properties, such as by passing the particles through a differential mobility analyzer or an impactor. In yet another example, the particles are size selected before being charged. In yet further examples, the aerosol is cooled before it is charged and the particles separated based on their flow properties, such as to produce a higher concentration of particles having a particular electrical mobility. In another example, the differential mobility analyzers have a sample flow rate and a sheath flow rate and the ratio of the sample flow rate to the sheath flow rate is greater than about 1:5, such as about 1:4.

The particles may be of a variety of shapes, compositions, charges, and sizes. In some examples, the particles are agglomerates of smaller particles. Typical particle samples have a mean particle size, such as cross-sectional diameter, between about 1 nm and about 100 μm, such as between about 50 nm and about 1 μm or between about 200 nm and about 700 nm. The shape of the particles can be expressed in terms of the volume-to-surface area ratio, or density fractal dimension. Typical particles have a fractal dimension of between about 1 and about 3, more typically between greater than 1 and about 2, such as between about 1.2 and about 1.8. Lower volume-to-surface area ratios, or density fractal dimensions, can indicate less spherical particles, such as more linear particles.

In some embodiments, the likelihood of a particle acquiring a certain number of charges in a charging process depends on its morphology. For example, more elongated particles may be more likely to acquire a second charge than spherical particles as, for the same particle mass, the second charge can be located farther from the first charge, thereby requiring less energy for the charging process. In further implementations, the particles are then separated based on their flow properties

In some embodiments, the particles are at least partially charge deformable. Charge deformable means that the particles change shape, such as elongating, when charged, such as with an electrostatic charge. Some embodiments of the present disclosure provide for charging particles, at least a portion of which are at least partially charge-deformable. Charging the particles thus alters the morphology of at least a portion of the particles. In further implementations, the particles are then separated based on their flow properties.

The present disclosure also provides a system for particle separation. The system includes a first differential mobility analyzer fluidly coupled to a second differential mobility analyzer. The first differential mobility analyzer is configured to produce an at least substantially monodisperse aerosol of

particles having a desired electrical mobility-to-charge ratio, the monodisperse aerosol comprising particles bearing one elementary charge and particles bearing multiple elementary charges. The second differential mobility analyzer is configured to select as its primary mode particles having an electrical mobility corresponding to the product of the desired electrical mobility-to-charge ratio and the number of elementary charges on the multiply-charged particles.

There are additional features and advantages of the subject matter described herein. They will become apparent as this specification proceeds.

In this regard, it is to be understood that this is a brief summary of varying aspects of the subject matter described herein. The various features described in this section and below for various embodiments may be used in combination or separately. Any particular embodiment need not provide all features noted above, nor solve all problems or address all issues in the prior art noted above.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram illustrating one embodiment of a process for separating particles having different morphologies.

FIG. **2** is a schematic illustration of particles of different morphologies being separated based on their charge.

FIG. **3** is a flowchart of an example of the disclosed method.

FIG. **4** is a flowchart of an example process for carrying out the disclosed method.

FIG. **5** is a schematic diagram of a system that can be used to separate particles of different morphologies based on their charge.

FIG. **6** is a schematic diagram of a system for soot generation, separation, and characterization.

FIGS. **7**(*a*)-**7**(*d*) provide graphs of the change in the number of agglomerate particles versus the change in the log of mass fractal dimension plotted against equivalent diameter (D_{eq}, nm) and SMPS mobility diameter (D_m, nm) number size distribution for (a) soot particles with D_m=220 nm and q=−e, (b) soot particles with D_m=220 nm and q=−2e, (c) soot particles with D_m=460 nm and q=−e, and (d) soot particles D_m=460 nm and q=−2e.

FIGS. **8**(*a*)-**8**(*d*) are electron microscopy images of for (a) soot particles with D_m=220 nm and q=−e, (b) soot particles with D_m=220 nm and q=−2e, (c) soot particles with D_m=460 nm and q=−e, and (d) soot particles D_m=460 nm and q=−2e.

DETAILED DESCRIPTION

Unless otherwise explained, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. In case of any such conflict, or a conflict between the present disclosure and any document referred to herein, the present specification, including explanations of terms, will control. The singular terms "a," "an," and "the" include plural referents unless context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise. The term "comprising" means "including;" hence, "comprising A or B" means including A or B, as well as A and B together. All numerical ranges given herein include all values, including end values (unless specifically excluded) and intermediate ranges.

Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present disclosure, suitable methods and materials are described herein. The disclosed materials, methods, and examples are illustrative only and not intended to be limiting.

"Aerosol" refers to a dispersion of particles in a fluid medium, such as a gas, or in a vacuum. In some examples, the gas is air. Aerosols may be formed by a variety of methods, including ablation, flame synthesis, spray drying of colloidal or precipitated particles, spray pyrolysis, and thermal evaporation. The particle concentration in the aerosol is typically selected to provide suitable particle separation in the method of the present disclosure, or based on how the particles will be used after separation. In some examples the particle concentration is between about 10^1 particles/cm^3 and about 10^{13} particles/cm^3, such as between about 10^4 particles/cm^3 and about 10^{11} particles/cm^3 or between about 10^7 particles/cm^3 and about 10^9 particles/cm^3.

"Flow properties" refers to the influence of electrostatic and/or electrodynamic forces by themselves or in combination with other forces such as inertial, viscous, magnetic, or gravitational forces, optionally with the use of spatial or temporal gates, on a particle's movement in a fluid medium or a vacuum. In one example, the flow property is electrical mobility. According to the present disclosure, flow properties can be influenced by external forces in order to separate particles based on their morphologies.

In one example, time-of-flight techniques, such as time-of-flight mass spectrometry, are used to separate particles based on electrodynamic forces. In another example, an electrostatic classifier is used to influence the flow properties of a particle using viscous and electrostatic forces. A Millikan apparatus, using gravity and electrostatic forces, can be used to separate particles.

"Mobility diameter," or D_m, is a parameter used to characterize particles and refers to the diameter of an equivalent sphere having the same electrical mobility as the particle in question, which may be nonspherical.

"Nanostructure" refers to a solid structure having a cross sectional diameter of between about 0.5 nm to about 500 nm. Nanostructures may be made from a variety of materials, such as carbon, silicon, and metals, including, without limitation, titanium, zirconium, aluminum, cerium, yttrium, neodymium, iron, antimony, silver, lithium, strontium, barium, ruthenium, tungsten, nickel, tin, zinc, tantalum, molybdenum, chromium, and compounds and mixtures thereof. Suitable materials that also are within the definition of nanostructures include transition metal chalcogenides or oxides, including mixed metal and/or mixed chalcogenide and/or mixed oxide compounds or carbonaceous compounds, including elemental carbon, organic carbon, and fullerenes, such as buckyballs, and related structures. In particular examples, the nanostructure is made from one or more of zinc oxide, titanium dioxide, gallium nitride, indium oxide, tin dioxide, magnesium oxide, tungsten trioxide, and nickel oxide.

The nanostructure can be formed in a variety of shapes. In one implementation, the nanostructures are wires, such as wires having at least one cross sectional dimension less than about 500 nm, such as between about 0.5 nm and about 200 nm. Nanowires can be nanorods, having a solid core, or nanotubes having a hollow core. In some implementations, the cross sectional dimension of the nanostructure is relatively constant. However, the cross sectional dimension of the nanostructure can vary in other implementations, such as rods or tubes having a taper.

As used herein, "particle" refers to a small piece of an element, compound, or other material. Particles that may be used in the present disclosure include those having a size,

such as a cross-sectional diameter, of between about 1 nm and about 100 μm, such as between about 50 nm and about 1 μm or between about 200 nm and about 700 nm. The shape or morphology of the particles can be expressed in terms of the volume-to-surface area ratio, or density fractal dimension. Typical particles have a fractal dimension of between about 1 and about 3, typically greater than 1 and less than 2, such as between about 1.2 and about 1.8. The particles may be of any form, such as powders, granules, pellets, strands, or flocculent materials. The particles may be individual, discrete units, agglomerations of multiple units, or mixtures thereof. Particle agglomerates can assume a number of shapes. As the number of particles in the agglomerate increases, the number of potential morphologies also typically increases. Even relatively small agglomerates typically can exist in a number of different morphologies. When the morphology plays a role in the function of the particles, morphological separation may be important, and difficult to achieve using prior methods.

The particles may be of any desired material that can be charged for the separation process, or that is mixed with such a material. For example, the particles may be, or include, carbonaceous materials, ceramics (such as metal borides, carbides, or nitrides), extenders, fillers, inorganic salts, metals, metal alloys, metal alkoxides, metal oxides, pigments, polymers, zeolites, or combinations and mixtures thereof. Specific examples of such materials include aluminum, antimony oxide, asbestos, attapulgite, barium sulfate, boehmite, calcium carbonate, chalk, carbon black, chromium, cobalt, copper, diatomaceous earth, fumed oxides, gold, halloysite, iron, iron oxides, kaolin, molybdenum, montmorillonite, nickel, niobium, palladium, platinum, silica, silica aerogels, silica sols, silicon, silver, tantalum, titania, titanium, titanium isopropoxide, zinc oxide, zinc sulfide, or alloys, mixtures, or combinations thereof.

In some examples, the particles can be used to form nanostructures, such as nanorods or nanotubes. The disclosed systems, apparatus, and methods can be used to separate particles, such as nanoparticles, having different morphologies and, optionally, other differences. In some examples, the particles are combustion particles, such as carbon black.

One particle property is electric charge. At a given temperature, particles typically have a Boltzmann distribution of positively charged, negatively charged, and neutral particles. Particles may be further charged by various mechanisms, including static electrification, such as electrolytic charging, spray electrification, or contact charging. Field charging may also be used. Other forms of charging include corona discharge, radioactive discharge, ultraviolet radiation, and flame ionization. In some implementations, a combination of charging mechanisms is used.

In a specific example, bipolar charging is used. In bipolar charging, positive and negative charges are applied to the particles, such as by interacting the particles with bipolar ions. The net charge on the particles following bipolar charging may be negative, positive, or neutral. When charged, the particles may have at least one charge, but potentially may be multiply charged.

The distribution of charges is typically related to temperature. In some examples, a sample is cooled prior to charging in order to produce a desired distribution. For example, higher temperatures may facilitate multiple morphologies being multiply-charged, which may make separation less efficient. Cooling the sample can increase the probability that the more linear morphologies are multiply-charged rather then more spherical morphologies.

In some embodiments, the particles are at least partially charge deformable. "Charge deformable" means that the particles change shape, such as elongating, when charged, such as with an electrostatic charge. Charge deformable particles are typically at least partially flexible. In some examples, particles elongate when a charge, or charges, is applied or increased. In another example, particles assume a more spherical shape when charge is removed or reduced.

The following equation provides a relationship between mobility and particle size:

$$Z_p = \frac{ieC_c}{3\pi\mu D_p} \quad (1)$$

In Equation 1, e is the elementary charge, i is the number of elementary charges carried by a particle (typically an integer), C_c is the slip correction factor (defined later in this disclosure), and μ is the gas viscosity. As can be seen from this equation, for a given mobility Z_p, more highly charged particles will have a larger D_p compared with less charged particles.

In various embodiments of the present disclosure, particles with a certain charge can be selected using forces that depend on the charge, such as electrostatic and/or electrodynamic forces by themselves or in combination with other forces such as inertial, viscous, or gravitational forces or with the use of spatial or temporal gates. In a specific example presented in the present disclosure, particles with a certain charge are selected using a differential mobility analyzer. The differential mobility analyzer uses a combination of viscous and electrostatic forces to select a combination of charge q and aerodynamic particle size with a spatial gate.

A schematic diagram of a process for separating particles based on flow properties **100** is presented in FIG. **1**. A sample source **110** produces a material **120** having a plurality of particles, at least a portion of which differ at least in their morphology, although the particles of the portion may differ in other properties, such as size.

The material **120** is typically dispersed in a carrier fluid, such as a gas. In one example, the gas is air. The concentration of the material **120** in the carrier gas may depend on a number of factors, such as the type of separator used in the process **100**, the flow rate of the material **120** through the separator, the properties of the material **120**, such as its size, size distribution, morphology, morphology distribution, or other chemical or physical properties. For example, in at least some processes it may be desirable to keep the concentration of the material **120** below a certain level to avoid undesired particle agglomeration.

A variety of methods are known to prepare suitable concentrations of particles **120** in a carrier. For example, particles, such as carbon black particles, can be produced by flame combustion. Ablation of solid materials is another technique that can be used to generate the particles **120**.

The material **120** is passed through a separator **130** that separates the material **120**, at least in part, based on morphology. Suitable separators **130** include those that can separate materials based on their flow properties, such as their electrical mobility. One suitable separator **130** that can separate particles on their electrical mobility is the differential mobility analyzer. Suitable differential mobility analyzers include the Series 3080 electrostatic classifiers, available from TSI, Inc. of Shoreview, Minn. Details of an instrument that allows relatively high particle concentrations to be used are described in Camata et al., "Deposition of Nanostructured Thin Film from Size-Classified Nanoparticles," NASA 5th Conference on Aerospace Materials, Processes, and Environ-

mental Technology (November 2003), incorporated by reference herein to the extent not inconsistent with the present disclosure. In some aspects, the process **100** separates the material **120** only on the basis of morphology. In other aspects, the process **100** separates the material **120** based on morphology and at least one other property, such as size or charge.

As shown in FIG. **1**, the separator **130** separates the material **120** into two subsets, one set **140** has a charge of xe and another set **150** has a charge of ye. In at least some examples, x and y are integers and the overall charge is xq or yq, where q is the elementary charge of $1.602176487\times10^{-19}$ C. The separator **130** may separate the material into more than two subsets. Each subset may have particles having only a single charge, or single distribution of charges, or may have multiple charges or charge distributions. At least one subset may have a random charge distribution.

Although FIG. **1** illustrates a single separator **130**, alternative embodiments of the system **100** may include multiple separators. When multiple separators **130** are used, the separators **130** may be the same or different. Multiple separators **130** may be desirable, for example, when the material **120** includes more than two morphologies or particle sizes that are desired to be separated. When multiple separators **130** are used, additional processes (not shown) may be performed on the material **120** after it exits the separator **130** and before it enters one or more additional separators. When multiple separators **130** are used, they may be present as discrete components or devices or may be a unitary device.

The system **100** optionally includes one or more upstream processes **160**. One upstream process may consist of size selection. Suitable impactors and virtual impactors are commercially available, such as the Sioutas Cascade Impactor from SKC Inc., of Eighty Four, Pa. and the Model 3306 Impactor Inlet from TSI Inc., of Shoreview, Minn. Size selection may be useful, for example, in providing an initial separation of the material **120** to remove undesired components, such as particles outside a desired particle range. In one example, size selection is accomplished using an impactor or a virtual impactor.

Upstream processes **160**, such as size selection, may be useful in reducing fouling of the separator **130** or in increasing separator **130** efficiency or producing more desirable subsets **140** or **150**.

The system **100** optionally includes one or more downstream processes **170**. Downstream processes **170** can include, but are not limited to, treatment, detection, or separation processes.

FIG. **2** is a schematic illustration of how particle properties may be used to separate particles of different morphologies. In the illustrated process **200**, two types of particles are shown. Particles **210** have a more spherical morphology and, if the particles **210** are of the same type, will have a particle mobility diameter (D_m) of x and a particle diameter (D_p), or size, of y. Particles **220** have a more linear morphology, giving rise to a smaller particle mobility diameter x', and a larger maximum particle dimension y'. Generally, the more linear a particle, the smaller it's D_m compared with a spherical particle of similar mass. Stated another way, the electrical mobility of linear particles is equivalent to that of a smaller sized sphere.

In process **230**, the particles **210** and **220** are charged. As shown in FIG. **2**, the more spherical particles **210** have a lower probability of being multiply-charged, and thus are shown as singly-charged particles **240**. More linear particles **220** have a higher probability of being multiply-charged and thus are shown as multiply-charged particles **250**. Separating the particles **240** and **250** in the process **260** based on charge thus has the effect of concentrating the two output streams **270** and **280** in particles of a particular morphology.

FIG. **3** illustrates an example **300** of the disclosed method. In step **310**, a first aerosol is charged, such as with bipolar charging. Charging process **310** produces a charge distribution for the particles in the aerosol. For example, when biopolar charging is used, some particles will be negatively charged, some particles will be positively charged, and some particles will be neutral. For charged particles, while the majority of the charged particles will have a single charge, a portion will be multiply-charged.

In step **320**, a portion of the particles in the aerosol are separated based on their flow properties. In a specific example that will be discussed in detail in the present disclosure, a differential mobility analyzer is used to separate the particles based on their electrical mobility. In this example, particles having a desired electrical mobility are selected away from other particles in step **320**.

In some configurations, the desired separation is completed in step **320**. In other examples, such as when the aerosol includes a larger variety of particle shapes and sizes, the particles selected in step **320** are subjected to an additional separation step.

In step **330**, the aerosol is charged again, such as using a bipolar charger. This charging typically erases the original charge distribution and applies a new charge distribution. In other words, the probability of a particle bearing one charge or bearing multiple charges is determined as if the particles were neutralized and in a similar state as prior to the first charging process **310**. Thus, those particles that were multiply-charged after step **310** are now likely to be singly-charged. The formerly multiply-charged particles, when charged with a single charge, now have an electrical mobility different than the particles which were singly-charged after step **310** and selected in step **320** (and which are likely to still be singly-charged after charging step **330**). Because the particles selected in step **320** now have different flow properties, they can be selected based on those properties, such as in another differential mobility analyzer, in step **340**. As the originally multiply-charged particles had a greater probability of being more linear, the effect of steps **320** and **340** is to separate those more linear particles from more spherically shaped particles.

FIG. **4** presents an example **400** of the disclosed method that may be used when sequential electrostatic classifiers (the combination of a neutralizer and a differential mobility analyzer) are used to carry out the method of FIG. **3**. In step **410**, the shape and particle size of the desired particles are determined. Hypothetically, assume that more linearly shaped particles with a mobility diameter of 400 nanometers are desired.

Because more linearly shaped particles are desired, it can be assumed that they have a higher probability of being multiply-charged after bipolar charging. In step **420**, the electrical mobility of the desired particles is determined for such particles bearing a single elementary charge. For simplicity, assume that this electrical mobility is simply the electrical mobility of the multiply-charged particles divided by the number of elementary charges carried by the particle. For example, for doubly-charged particles in the hypothetical, the electrical mobility would be 200 nanometers. In practice, the relationship between electrical mobility and charge has a more complicated relationship, but can be calculated by:

$$Z_p = \frac{neC_c(d_m)}{3\pi\eta d_m} \quad (2)$$

In Equation 2, Z_p is the electrical mobility, n is the number of elementary charges on the particle, $C_c(d_m)$ is the Cunningham slip correction factor, η is the gas dynamic velocity, and d_m is the electrical mobility diameter. Additional details on electrical mobility and other particle properties can be found in DeCarlo et al., Aerosol Science and Technology, 38, 1185-1205 (2004), incorporated by reference herein to the extent not inconsistent with the present disclosure.

In step **430**, the primary mode of a first electrostatic classifier is set to the electrical mobility determined in step **420**; 200 nanometers in the hypothetical. When a charged sample is passed through the differential mobility analyzer portion of the electrostatic classifier, particles having an electrical mobility corresponding to integer multiples of the primary mode will be transmitted, that is, having a particular electrical mobility-to-charge ratio. In the hypothetical, the desired particles having an electrical mobility of 400 nanometers are selected, as are singly-charged particles having an electrical mobility of 200 nanometers.

The primary mode of a second electrostatic classifier is set to the electrical mobility of the desired particles in step **440**. As explained in conjunction with FIG. **3**, particles from the first electrostatic classifier will be subjected to a new charge distribution when passed through the neutralizer of the second electrostatic classifier. Because the desired particles, the majority of which are now singly-charged, have an electrical mobility different than the other particles selected by the first electrostatic classifier (the majority of which are also singly-charged), the particles can again be separated. In the hypothetical, the desired more linearly shaped particles can be separated from other aerosol components.

FIG. **5** illustrates a more specific embodiment **500** of the system **100** of FIG. **1** that can carry out the process shown in FIG. **2**. In the system **500**, two electrostatic classifiers are used to at least partially separate a sample into different morphologies. A sample source **508** is fluidly coupled to a pretreatment unit **510**, such as an impactor. An exit stream from the pretreatment unit **510** is fluidly coupled to a first neutralizer **512**. In some examples, the first neutralizer **512** is a Model 3077 or 3077A neutralizer, available from TSI Inc., of Shoreview, Minn. The neutralizer **512** is coupled to a sample inlet **514** of a first differential mobility analyzer **516**. Together, the first neutralizer **514** and the first differential mobility analyzer **516** form a first electrostatic classifier **518**.

The first differential mobility analyzer **516** includes an inner rod electrode **520** disposed in a housing **522**. The housing **522** is typically cylindrical but may be constructed in other geometric shapes. An outer electrode **524** is located adjacent the housing **522**. In some configurations, the outer electrode **524** and the housing **522** are the same structure, in other configurations they are different structures.

The section **526** between the outer electrode **524** and the inner electrode **520** forms a flow sheath. The sheath **526** is fluidly coupled to a source of sheath fluid **528** through a sheath fluid inlet **530** at a first end **532** of the differential mobility analyzer **516**.

At a second end **534** of the differential mobility analyzer **516**, an exhaust outlet **536** is located at the periphery of the housing **522**. A central sample outlet **538** is optionally fluidly coupled to an intermediate treatment unit **540**. The intermediate transfer unit **540** may, for example, be used to condition or alter the particles before further separation or processing.

The sample outlet **538** is further fluidly coupled to a second electrostatic classifier **542**. The second electrostatic classifier **542** includes a neutralizer **544** and a differential mobility analyzer **546** that includes a sample inlet **548**, a housing **550** having a first end **552** and a second end **554**, an inner electrode **556**, an outer electrode **558**, a sheath fluid source **560**, a sheath fluid inlet, **562**, a sheath **564**, an exhaust outlet **566**, and a sample outlet **568**. In at least one configuration, the components of the electrostatic classifier **542** are generally as described for the electrostatic classifier **518**.

In some examples of the system **500**, the intermediate transfer unit **540** is omitted and the sample outlet **538** is directly coupled to the second electrostatic classifier **542**. In yet further embodiments, the neutralizer **544** is omitted and the sample outlet **538**, or the intermediate unit **540**, if used, is connected directly to the sample inlet **548**.

The system **500** operates as follows. A sample source **508** produces or transmits a mixed sample to the pretreatment unit **510**. When the pretreatment unit **510** is an impactor, the impactor separates particles having a predetermined size range and transmits the refined sample to the neutralizer **512**.

The neutralizer **512** applies charge to the sample particles. After passing through the neutralizer **512**, the particles will have a charge that depends, at least to an extent, on the size and morphology of the particle. As an example, seven types of particles are illustrated in FIG. **5**

The sample includes particles having a first morphology and a first electrical mobility-to-charge ratio and bearing one or more negative charges **570**, one or more positive charges **572**, or being neutral **574**. Similarly, particles of a second morphology and having the first electrical mobility-to-charge ratio are positively charged **576**, negatively charged **578**, or are neutral **580**. In a specific example, the positively charged particles of the first morphology **572** bear two elementary charges and the positively charged particles of the second morphology **576** bear a single elementary charge. The sample also includes particles **582** of a second electrical mobility-to-charge ratio, the charges of which are not specified in FIG. **5**.

When the inner electrode **520** is negatively charged and the outer electrode **524** is positively charged, the negatively charged particles **570**, **578** will be drawn towards the outer electrode **524**. At least a portion of the particles **570**, **578** may impact the outer electrode **524**. Particles **570**, **578** that do not impact the electrode **524** have a trajectory that causes them to enter the exhaust outlet **536**. In other configurations, the charges on the electrodes **520**, **524** are reversed or one is uncharged.

The neutral particles **574**, **580** are not attracted to either of the electrodes **520**, **524** and have a trajectory though the sheath **526** that carries them to the exhaust outlet **536**.

The positively charged particles **572**, **576** are attracted towards the inner electrode **520**. Some of the particles **572**, **576** have an electrical mobility-to-charge ratio that imparts a trajectory in the sheath **526** that carries the particles **572**, **576** to the sample outlet **538**. For example, when the first differential mobility analyzer is set to select as its primary mode particles **576** (that is, singly-charged particles having the mobility diameter of the particles **576**), it will also transmit particles **572**, which, when doubly-charged, have a mobility diameter that is approximately double that of the particles **576**. Particles outside of the selected electrical mobility-to-charge ratio **582** have a trajectory that carries them to the exhaust outlet **536**, regardless of their charge.

Particles in the exhaust outlet **536** may be removed from the system **500** or, in some configurations, returned to the differential mobility analyzer **516**, such as with the sheath fluid source **528**. When returned to the differential mobility

analyzer **516**, the exhaust from outlet **536** may be treated, such as being filtered to remove all or a portion of the particles carried through the outlet **536**. The particles **572**, **576** passing through the sample outlet **538** are, at least in some implementations, carried through the intermediate treatment unit **540**. In a particle example, the intermediate transfer unit **540** changes the morphology of one or more of the particles **572**, **576**, such as by applying a charge to deform the particles.

In at least some configurations, the particles **572**, **576** from the outlet **538** or the intermediate transfer unit **540** pass through the neutralizer **544**. The neutralizer **544** imparts a new charge distribution to the particles **572**, **576**. The differential mobility analyzer **546** is configured to select singly-charged particles having the mobility diameter of particles **572**.

As shown in FIG. **5**, particles **572** are transmitted by the differential mobility analyzer **546** through the sample outlet **568**, where the particles **572** may be collected, detected, or subjected to additional processing steps. The particles **576** no longer have a mobility diameter that is selected by the differential mobility analyzer **546** and pass into the exhaust outlet **566**. The particles **576** can then be collected, detected, subjected to additional processing steps, or merely discarded.

The properties of the differential mobility analyzers **516**, **546** can be adjusted to provide a desired separation. The particle diameter, D_p, can be related to other parameters of a differential mobility analyzer by Equation 3 below:

$$\frac{Dp}{C} = \frac{2ne\bar{V}L}{3\mu q_{sh}\ln\frac{r_2}{r_1}} \tag{3}$$

In Equation 3, C is the Cunningham slip correction factor (defined below), n is the number of elementary charges on a particle (typically an integer), e is the elementary charge, V is the average voltage on the inner electrode, L is the length between the sample inlet and the sample selection outlet, μ is the gas viscosity, q_{sh} is the sheath air flow rate, r_2 is the outer radius of the annular space (the distance between the center of the differential mobility analyzer and the outer electrode) and r_1 is the inner radius of annular space (the distance between the center of the differential mobility analyzer and the outer surface of the inner electrode).

The Cunningham slip corrected factor is defined in the following equation:

$$1+\mathrm{Kn}[\alpha+\beta^{-\gamma/Kn}] \tag{4}$$

In Equation 4, α is 1.42, β is 0.558, and γ is 0.999. Kn is the Knudsen Number, or $2\lambda/D_p$, where λ is the gas mean free path, or:

$$\lambda_r\left(\frac{P_r}{P}\right)\left(\frac{T}{T_r}\right)\left(\frac{1+S/T_r}{1+S/T}\right) \tag{5}$$

In Equation 5, S is the Sutherland constant, T is the temperature, P is the particle size, and T_r, P_r, and λ_r are reference temperature, particle diameter, and mean free path values.

The gas viscosity, μ, is defined as:

$$\mu_r\left(\frac{T_r+S}{T+S}\right)\left(\frac{T}{T_r}\right)^{\frac{3}{2}} \tag{6}$$

From Equation 3, it can be seen that the parameters of the differential mobility analyzers **516**, **546** can be adjusted to select particles having a particular number of elementary charges n. For example, Equation 3 suggests that higher flow rates q h or lower inner electrode voltages V will favor selection of particles having higher numbers of elementary charges.

As explained above, the first differential mobility analyzer **516** is used to select, from a bulk stream of particles, those having a specific electrical mobility-to-charge ratio. In order to transmit a high amount of such particles, the first differential mobility analyzer **516** is typically configured to transmit singly-charged particles but will also transmit multiply-charged particles.

The operational parameters of the differential mobility analyzers **516**, **546** depend on a number of factors, such as the particle sizes entering the analyzers and their charge or charge distribution. For materials whose properties are known, particles having the morphology and size desired influence the operational parameters of the differential mobility analyzers **516**, **546**, such as sample flow rate, sheath flow rate, and electrode charge. Those operational parameters can then be varied to produce a combination that selects the desired particles. For example, setting the electrode charges at a particular value requires the other parameters to be set at complementary values for a particular particle size and particle charge.

The inner electrode **520** and outer electrodes typically have a charge of between about 0 V and about 50,000 V, such as between about 1000 V and about 25,000 V or between about 5000 V and about 15,000 V. The sample flow rate is typically between about 0.05 l/min and about 50 l/min, such as between about 0.5 l/min and about 10 l/min or between about 1 l/min and about 5 l/min. The sheath flow rate is typically between about 0.5 l/min and about 500 l/min, such as between about 5 l/min and about 100 l/min or between about 10 l/min and about 50 l/min.

The ratio of sample-to-sheath flow may also influence the separation of particles. For example, as the sheath flow increases relative to the sample flow, a finer separation (a narrow range of selected particles) can be obtained. However, at higher sheath flow rates, the concentration of selected particles is typically lower. Thus, when higher concentrations or larger numbers of particles are desired, it may be beneficial to lower sheath flow rates (that is, use higher sample-to-sheath flow ratios). In some examples, the sample-to-sheath flow rate is between about 1:2 and about 1:20, such as between about 1:3: and about 1:0. In a more specific example, the sample-to-sheath flow ratio is about 1:4. When higher ratios are used the particles can be pretreated to account for the potentially coarser separation, such as by passing the particles through an impactor or other size-selection device.

The following Example is provided to illustrate specific features of one disclosed embodiment of the present disclosure. A person of ordinary skill in the art will understand that the scope of the present disclosure is not limited to these particular features.

EXAMPLE

This Example demonstrates that aspherical particles (in particular, fractal-like agglomerates) can be electrically

charged and that particle morphology is related to the charge on the particle. The separator used in this Example is an electrostatic classifier ("EC"), a neutralizer combined with a differential mobility analyzer.

The EC utilizes a combination of a viscous and electrostatic force to select a combination of charge q and aerodynamic particle size with a spatial gate. Although ECs are used for particle sizing and for the generation of monodisperse aerosols in the size range from 0.005 to 1.0 μm, they do not appear to have been used to separate particles based on morphology.

Typically, an EC passes a polydisperse sample through a neutralizer, such as a Kr-85 radioactive charge neutralizer, where particles attain a Boltzmann charge distribution. A known size fraction of charged particles are extracted using a spatially varying electric field. The velocity of the extracted fraction of particles inside an EC is a function of the field strength and of the particle electrical mobility, which is in turn a function of the particle net charge (q) and mobility diameter (D_m). If an EC is set to predominantly size-select particles with a specific mobility diameter D_m and q=−e, it also transmits a certain percentage of particles with charge −ie and mobility diameter ~−ieD_m, where i is an integer number. At any EC setting, depending on the polydispersivity of the particle size distribution, multiple particle size modes are being transmitted with up to three modes being significant for particle diameters below 0.5 μm.

In this Example, ECs were configured to select cluster-dilute agglomerates with identical D_m but carrying a) predominantly q=−e, and b) predominantly q=−2e. The cluster-dilute regime is defined as when the ratio of the mean cluster nearest-neighbor separation to cluster size is large. Quantitative analysis of agglomerate morphology with the help of a Scanning Electron Microscope ("SEM") and image processing techniques showed that agglomerates with predominantly q=−2e possess very different ensemble morphology when compared to those with q=−e. This morphology difference was observed for both short-chained (~220 nm) and submicron-sized (~500-1000 nm) agglomerates.

System Details:

Nanometer-scale soot aerosol agglomerates were produced using flame synthesis, which is a well-established industrial technology for producing aerosols on a large-scale. A schematic diagram of the experimental set-up is illustrated in FIG. **4**. Soot agglomerates were produced by a premixed flame supported on a cooled porous frit burner (Holthuis & Associates, Sebastopol, Calif.) through combustion of ethene (1.4-4.2 l min^{-1} STP) and oxygen (2.0-4.5 l min^{-1} STP) premixed with a dilution flow of nitrogen (1.0-5.0 l min^{-1} STP) and surrounded by an N_2 sheath flow (~25 l min^{-1} STP).

The premixed gases were passed through a 6-cm diameter porous frit, which in turn was surrounded by a 0.5-cm wide annular sheath region through which N_2 was passed. The flame was maintained at an equivalence ratio ϕ of 2.8. The equivalence ratio ϕ is defined as the fuel to oxygen ratio divided by the stoichiometric fuel-to-oxygen ratio which can be written as:

$$\varphi = \frac{n_{fuel}/n_{oxygen}}{(n_{fuel}/n_{oxygen})_{stoich}} \quad (7)$$

In Equation 7, n stands for the number of moles of fuel or oxygen. In this Example, the flame was maintained at a fuel-rich ϕ of 2.8 to obtain soot with a high ratio of black-carbon to organic carbon. The premixed gas and sheath flows were contained by glass housing shaped to minimize convective mixing, thereby ensuring that the flame stoichiometry was well-characterized at the point of sampling.

Prior to sampling, the flatness of the flame, i.e. uniformity across a given flame cross-section was checked. A diagram of the sampling tip is shown in the inset to FIG. **6**. The sampling tip consisted of two concentric stainless steel tubes with particles carried up the inner tube while a separate nitrogen carrier gas (14.5 l min^{-1} STP) was passed down the outer tube and then back up the inner tube. The gas flow around the lip of the inner tube helped reduce soot buildup in this region and dilute the particle concentration.

Particle sampling was carried out in the overfire region of the flame, where the characteristic flame residence times are roughly an order of magnitude longer than the laminar smoke point residence time. Soot particles in the long residence time regime are fully formed into agglomerates and their properties are fairly independent of position, which facilitates sampling of a steady and uniform distribution of particles.

The gas flow carrying the diluted soot particles was then passed through an impactor to remove particles larger than about 5 μm in diameter. Sample flow exiting the impactor was directed through either path A containing a single EC, or through path B containing two ECs in series (FIG. **6**). The particles were bipolarly charged using a neutralizer (Model Kr-85, TSI Inc., Shoreview, Minn.) before entering any of the identical ECs (Model 3080, TSI Inc., Shoreview, Minn.).

Two set of experiments were carried out using the set-up with identical operating conditions for studying charge-related differences in agglomerate morphology corresponding to D_m=220 and 460 nm respectively. For each set of experiments, the EC in path A was set to predominantly size select soot particles with q=−e and a D_m (either 220 or 460 nm). In path B the sheath flow-rate of the first EC was adjusted such that the second (q=2e) mode of particles exiting the EC corresponded to the D_m in path A. In other words, the second EC size selected as its predominant (q=−e) mode the q=−2e mode particles exiting the first EC. For example, in order to size select doubly-charged D_m=220 nm particles in path B, the 1st EC was set to select singly-charged particles with D_m=142 nm, which would also transmit doubly-charged particles with D_m=220 nm. These particles were neutralized and sent to the 2nd EC, which was set to select singly-charged particles with D_m=220 nm.

In this Example, the D_m=460 nm particles were classified using ECs at sheath flow rates of around 5 l min^{-1}, and the D_m=220 nm particles were classified at flow rates of around 8 l min^{-1}. The sheath flow rates of the ECs and the electrical fields, during both set of our experiments, were maintained nearly constant so that they would have a negligible effect on particle alignment. There was a sharp decrease in the particle concentration exiting pathway B, likely because of use of charge neutralizers before both the ECs. Accordingly, the aerosol to sheath flow-rate ratios in the ECs for both the pathways were maintained at around 1:4, thereby assuring sufficiently high particle concentrations in path B. Under these flow conditions, the resolution of the EC in path A was approximately ±30%. The serial combination of the two ECs in path B yielded a resolution of approximately ±20%. The ECs were calibrated using National Institute of Standards and Technology (NIST) certified Polystyrene Sphere Latex (PSL) particle size standards.

The particle flow exiting each pathway was isokinetically split into a particle sampling unit for SEM, and a scanning mobility particle sizer ("SMPS," Model 3936, TSI Inc., Shoreview, Minn.). The SMPS, which consists of an EC and a condensation particle counter (CPC), yields the particle num-

ber size distribution in terms of a Gaussian expression for particles with D_m<1000 nm. In this study the flow rate of the SMPS was set to measure only particles smaller than D_m=670 nm. For each set of experiments, both the SMPS and the SEM filter sampling were synchronized for one pathway at a time during each set of experiments.

For SEM analysis, soot particles were impacted onto 10-μm thick nuclepore clear polycarbonate 13-mm diameter filters (Whatman Inc., Chicago, Ill.) mounted on Costar Pop-Top Membrane holders (Corning Inc., Corning, N.Y.). An oil-free pump was used to draw soot particles at a flow rate of 2 l/min STP through copper tubing onto the nuclepore filters. The filter exposure time was adjusted to yield a moderate filter loading conducive for performing image analysis of individual agglomerates.

After sampling, the filter samples were kept in refrigerated storage and later prepared for SEM analysis by coating them with a 1-nm thick layer of platinum to prevent particle charging during SEM analysis. The coated filters were analyzed using a Hitachi Scanning Electron Microscope (Model S-4700).

SEM analysis may change the shape of particles through heat damage and physical damage. Heat damage evaporates semi-volatile components from the filter due to the high accelerating voltage of the electron beam (>20 kV) operating under vacuum conditions. Physical damage distorts the original particle shape because of particle charging by the electron beam. In this Example, a relatively moderate accelerating voltage of 20 kV was used for most images. Compared to lower accelerating voltages, the use of 20 kV improves imaging of the surface and internal structure of the particles. At this operating voltage, shape distortion due to charging was observed in less than 3% of the aggregates.

Results and Discussion

Two-dimensional (2-d) SEM images of about 300-400 soot agglomerates corresponding to each diameter and net charge were analyzed for morphology and shape quantification using commercial image analysis software (Digital Micrograph 3, Gatan Inc., Pleasanton, Calif.) and custom image processing routines.

An empirical formula for calculating the three dimensional (3-d) mass fractal dimension D of agglomerates is:

$$N = k\left(\frac{L_{max}}{d_p}\right)^D \tag{8}$$

In Equation 8, N is the number of monomers constituting the agglomerate, d_p is the mean monomer diameter, L_{max} is the maximum projected length of the agglomerate, and k is an empirical constant. For soot particles formed via dilute diffusion limited agglomeration processes, such as in a flame, D<2 and the projected 2-d D can be assumed to be approximately equal to the 3-d D.

However, for a finite-sized, 3-d fractal agglomerate, it has been found that parts of the agglomerate can randomly screen other parts during 2-d imaging. This screening can be corrected for through a calculation of N as:

$$N = \left(\frac{A_{agg}}{A_{mon}}\right)^\kappa \tag{9}$$

In Equation 9, a value of κ=1.10 is used to account for the 2-d screening effect, A_{agg} is the agglomerate projected area, and A_{mon} is the mean cross-sectional monomer area. Particle properties quantified using image analysis include A_{agg}, A_{mon}, d_p, and L_{max} as previously defined and maximum projected width W_{max} normal to L_{max}. Distribution of agglomerate projected area equivalent diameter D_{eq}, defined as the diameter of a circle of the same area as the particle under consideration, was calculated for all individual agglomerates and compared to the D_m distribution of the SMPS.

FIGS. **7**(*a*) and **7** (*b*) illustrate that the normalized number size distribution plot of D_{eq} and D_m (measured by SMPS) for q=−e and q=−2e particles corresponding to D_m=220 nm, while FIGS. **7**(*c*) and **7**(*d*) present similar plots for particles corresponding to D_m=460 nm. The predominant modes are comparable in each case. Higher modes could not be compared for 460 nm agglomerates, since the SMPS measures only particle diameters below 670 nm. The predominant peaks of the SEM D_{eq} number size distribution in FIG. **7** scale with the SMPS D_m distribution as D_{eq}~D_m^{α}, where α is the exponent characterizing the power law relationship. For both size distributions, α was found to be approximately one. These empirical relationships helped to specifically segregate out only those particles from SEM images which were centered around 220/460 nm for morphology analysis. The larger particles corresponding to the multiply-charged modes were not included for morphology analysis.

Mass fractal dimension D for the agglomerates was calculated using a) Equation 7, and b) the box counting technique. The box counting technique involves calculating the number of cells required to entirely cover a particle using grids of cells of varying size. The logarithm of the number of occupied cells versus the logarithm of the size of one cell gives a line whose gradient corresponds to the fractal dimension of the particle.

Two shape descriptors, aspect ratio and roundness, were calculated from the projected particle properties. These descriptors are sensitive to particle elongation. The scaling exponent β of the power-law relationship between L_{max}~D_{eq}^{β}, another parameter indicative of particle elongation, was also calculated for each of the agglomerates.

For spherical particle charging in a bipolar ionic environment, the Boltzmann distribution is a good approximation for calculating the fraction of particles carrying charge −ie, where i is an integer greater than or equal to. For D<2 agglomerates the same approximation, after a slight modification in its formulation, was also found to hold good within 10%. The modification replaced the physical diameter term in the Boltzmann distribution expression with a parameter called the charging equivalent diameter D_{qe} for fractal-like agglomerates.

The D_{qe} of the individual agglomerates was calculated, which in turn is a direct representative of the average net-charge residing on the agglomerates. Each D_{qe} was then scaled with its respective D_{eq} (which is approximately equal to D_m) as D_{qe}~D_{eq}^{γ}, where γ is the power law relationship exponent. Table 1 lists the mean values of all the analyzed 2-d morphological parameters from SEM images of particles with q=−e and q=−2e, and corresponding to D_m=220 nm and 460 nm respectively.

The analysis results summarized in Table 1 imply that for soot agglomerates produced under similar flame conditions and possessing the same mobility diameter, the morphology of doubly-charged (q=−2e) particles is distinctly different from that of singly-charged (q=−e) particles. The lower values of fractal dimensions and shape descriptors suggest a more elongated and open morphology for q=−2e particles compared to q=−e particles, which possess more compact and rounded morphology. Typical morphologies of singly and doubly-charged agglomerates for mobility diameters of 220

nm and 460 nm are shown in FIG. **8**. The values of D observed in this study for the singly-charged particles, of D_m=220 nm and 460 nm, correspond with previously reported values of D for soot agglomerates grown via diffusion-limited-agglomeration process in pre-mixed flames.

TABLE 1

Calculated values of agglomerate morphological properties

D_m and q	A (D_{eq}~D_m^{α})	β (L_{max}~D_{eq}^{β})	γ (D_{qe}~D_{eq}^{γ})	D (using Equation 1)	D (Box-counting method)	Aspect Ratio	Roundness
220 nm q = −e	1.01 ± .01	1.19 ± .03	1.14 ± .04	1.63 ± .04	1.75 ± .10	0.66 ± .14	0.73 ± .14
220 nm q = −2e	1.01 ± .01	1.43 ± .06	1.26 ± .03	1.43 ± .05	1.46 ± .11	0.51 ± .15	0.59 ± .15
460 nm q = −e	1.15 ± .02	1.21 ± .05	1.10 ± .05	1.70 ± .07	1.77 ± .12	0.73 ± .16	0.68 ± .16
460 nm q = −2e	1.1 ± .01	1.55 ± .04	1.34 ± .05	1.3 ± .06	1.41 ± .10	0.47 ± .14	0.41 ± .14

The higher value of the charging equivalent diameters for q=−2e agglomerates suggest more over-equilibrium charge deposited on them than their counterpart agglomerates with q=−e. This observation is can be explained by considering that the likelihood of a particle acquiring a certain number of charges in the charging process depends on its morphology. Elongated particles are more likely to acquire a second charge than spherical particles because, for the same particle mass, the second charge can be located at a larger distance from the first charge. The larger separation between the charges requires less energy for charging to occur and increases the charging probability. Lower temperatures may produce even better charge separation, further increasing the charging probability.

It is to be understood that the above discussion provides a detailed description of various embodiments. The above descriptions will enable those of ordinary skill in the art to make and use the disclosed embodiments, and to make departures from the particular examples described above to provide embodiments of the methods and apparatuses constructed in accordance with the present disclosure. The embodiments are illustrative, and not intended to limit the scope of the present disclosure. The scope of the present disclosure is rather to be determined by the scope of the claims as issued and equivalents thereto.

We claim:

1. A method for separating particles, comprising:

dispersing a plurality of particles in a fluid to form an aerosol, a portion of the particles having a first morphology and a portion of the particles having a second morphology;

charging at least a portion of the particles to produce a charged aerosol, the charged aerosol comprising particles having a first electrical mobility-to-charge ratio, comprising particles of the first morphology and particles of the second morphology, and particles having a second electrical mobility-to-charge ratio;

separating the particles of the first electrical mobility-to-charge ratio from the particles of the second electrical mobility-to-charge ratio, the separated particles of the first electrical mobility-to-charge ratio being selected particles;

charging the selected particles to produce particles of the first morphology having a first electrical mobility and particles of the second morphology having a second electrical mobility; and

separating particles of the first electrical mobility from particles of the second electrical mobility.

2. The method of claim **1**, wherein separating particles of the first electrical mobility-to-charge ratio from particles of the second electrical mobility-to-charge ratio comprises passing the aerosol through a first differential mobility analyzer.

3. The method of claim **2**, wherein separating particles of the first electrical mobility from particles of the second electrical mobility comprises passing the aerosol through a second differential mobility analyzer.

4. The method of claim **3**, wherein the second differential mobility analyzer selects as its primary mode the electrical mobility of a multiply-charged particle having the first electrical mobility-to-charge ratio.

5. The method of claim **3**, wherein the first and second differential mobility analyzers have a sample flow rate and a sheath flow rate and the ratio of the sample flow rate to the sheath flow rate is greater than 1:5.

6. The method of claim **1**, wherein charging the aerosol produces a distribution of charges, and the method further comprising cooling the aerosol to produce a higher concentration of particles having the first electrical mobility.

7. The method of claim **1**, wherein the first and second morphologies are differently shaped agglomerates.

8. A method for separating particles, comprising:

dispersing a plurality of particles in a fluid to form an aerosol, a portion of the particles having a first morphology and a portion of the particles having a second morphology;

applying a charge to at least a portion of the particles to produce a charged aerosol, the particles in the charged aerosol being neutral or charged;

passing the charged aerosol through a separator, the particles having flow properties as they pass through the separator;

altering the flow properties of at least a portion of the particles; and

separating at least a portion of the particles of the first morphology from the particles of the second morphology to produce a product stream having a higher concentration of particles of the first morphology and an exhaust stream having a higher concentration of particles of the second morphology.

9. The method of claim **8**, wherein altering flow properties of at least a portion of the particles comprises passing the charged aerosol proximate a first charged electrode, the first charged electrode attracting a greater proportion of particles of the first morphology than particles of the second morphology.

10. The method of claim **9**, wherein altering flow properties of at least a portion of the particles further comprises passing the particles proximate a second charged electrode, the first charged electrode and the second charged electrode altering the flow path of at least a portion of the particles of the first morphology such that the product stream is concentrated in particles of the first morphology.

11. The method of claim **8**, wherein altering the properties of at least a portion of the particles comprises passing the particles through a flow chamber having a first outlet and a second outlet, the product stream passing through the first outlet and the exhaust stream passing through the second outlet.

12. The method of claim **11**, wherein the flow chamber comprises a differential mobility analyzer.

13. The method of claim **8**, wherein the aerosol is polydisperse in particle electrical mobility and comprises particles having a first electrical mobility and particles having a second electrical mobility, the second electrical mobility being any electrical mobility other than the first electrical mobility, the particles of the first and second morphologies having the first electrical mobility, and wherein separating particles of the first morphology from particles of the second morphology comprises:

separating particles having the first electrical mobility from particles having the second electrical mobility to produce an at least substantially electrical mobility monodisperse stream of particles of the first electrical mobility; and

separating particles having the first morphology from the monodisperse stream.

14. The method of claim **13**, wherein separating particles having first electrical mobility comprises passing the aerosol thorough a differential mobility analyzer.

15. The method of claim **13**, wherein separating particles having the first morphology from the monodisperse stream comprises passing the monodisperse stream through a differential mobility analyzer.

16. The method of claim **15**, wherein passing the monodisperse stream through a differential mobility analyzer comprises charging the monodisperse stream.

17. A method for separating particles, comprising:

charging an aerosol comprising particles of a first morphology and a second morphology to produce a first distribution of a flow property;

separating particles based on the first distribution;

charging the aerosol to produce a second distribution of a flow property; and

separating particles based on the second distribution;

whereby separating particles based on the first and second distributions separates particles of the first and second morphologies.

18. The method of claim **17**, wherein the flow property is electrical mobility.

19. The method of claim **18**, further comprising cooling the aerosol to influence the first distribution and enhance separation of the first and second morphologies.

20. The method of claim **19**, wherein charging the aerosol to produce a second distribution of a flow property comprises forming a polydisperse sample in the flow property from a monodisperse sample in the flow property.

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